TIME ACTIVITIES AT THE BIPM

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Abstract

The generation and dissemination of International Atomic Time, TAI, and of Coordinated Universal Time, UTC, are explicitly mentioned in the list of the principal tasks of the BIPM, recalled in the Comptes Rendus of the 18th Conférence Générale des Poids et Mesures, in 1987. These tasks are fulfilled by the BIPM Time Section thanks to international cooperation with national timing centers, which maintain, under metrological conditions, the clocks used to generate TAI. Besides the current work of data collection and processing, research activities are carried out in order to adapt the computation of TAI to the most recent improvements occurring in the time and frequency domains. Studies concerning the application of general relativity and pulsar timing to time metrology are also actively pursued. This paper summarizes the work done in all these fields and outlines future projects.

INTRODUCTION

The Comité International des Poids et Mesures, CIPM, discussed the role of the Bureau International des Poids et Mesures, BIPM, in the 1980s and its conclusions were made known in the Convocation to the 18th Conférence Générale des Poids et Mesures [1], in the following terms:

"The purpose of the BIPM is to provide the physical basis necessary to ensure worldwide uniformity of measurements. Therefore, its principal tasks are:

- *to establish and disseminate the International Atomic Time, and, in collaboration with the appropriate astronomical organizations, Coordinated Universal Time;*
- *to furnish whatever help is possible in the organization of [those] international comparisons which, although not carried out at the BIPM, are carried out under the auspices of a Comité Consultatif;*
- *to ensure that the results of international comparisons are properly documented and, if not published elsewhere, are published directly by the BIPM... "*

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The definition of TAI was approved by the Comité International des Poids et Mesures in 1970, and recognized by the Conférence Générale des Poids et Mesures, CGPM, in 1971. It reads as follows:

International Atomic time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units.

In 1988, responsibility for TAI was transferred to the Time Section of the BIPM, according to one of the explicit missions recalled above.

From its definition, TAI is the result of a collective effort. It calls for the maintenance of atomic clocks in national timing laboratories, and for international comparisons between these clocks. One has thus established an exchange in which: * timing centres produce time transfer and clock data and send it to the BIPM, * the Time Section of the BIPM produces TAI, distributes it as time corrections to national time scales, and then publishes international time comparisons.

> *The efficiency of this organization and the quality of its results rely upon the care and the rigor of the work effected in the contributing laboratories and at the BIPM, and upon a continuous, positive, and fruitful dialogue between both parties.*

The Time Section of the BIPM is helped in its work in two ways:

- The Comité Consultatif pour la Définition de la Seconde, CCDS, creates working groups on specific topics such as Improvement of TAI, GPS Standardization, and Two–Way Satellite Time Transfer. The membership of these groups includes experts and members of the staff of the Time Section. Recommendations are issued and proposed for adoption to the CCDS, and then the CIPM and the CGPM, after extended discussions. This procedure makes it possible for the Time Section to keep itself informed about new techniques or studies. The Recommendations which are passed also give a formal guide to its work.
- The Time Section of the BIPM has at its disposal a time laboratory including two cæsium clocks and several GPS time receivers. Most of this equipment is on loan from private companies or from national timing centres. Data taken at the BIPM are not introduced in the TAI computation, but are simply analyzed for specific studies. This work provides a background of practical experience which sensitizes the Section to the problems of gathering data and allows it to make better use of that reported from outside.

The organization of the work at the Time Section is described in Fig. 1. The main objectives are perfectly clear and concern, as already stated, the generation and dissemination of TAI and UTC. However, they can easily be extended to the production of good realizations of the Terrestrial Time, TT, as defined by the International Astronomical Union, IAU, in 1992

[2]. These objectives imply that current activities centre on the regular production of TAI and on clock comparisons. More fundamental investigations are also carried out about time scale algorithms, time transfer methods, pulsar timing, and general relativity. This is described in the following sections.

GENERATION OF TAI AND UTC

As is well known, TAI is obtained through the computation of a weighted average of clock readings [3]. The main algorithm, optimized for long-term stability, treats as a whole blocks of data collected over a two-month period, and produces in deferred-time a free time scale, EAL. External to this main algorithm, accuracy is ensured by frequency steering corrections, which are applied to EAL to obtain TAI, after comparison with the best primary frequency standards.

The 230 contributing clocks are kept in 46 national time centers spread world-wide. At present, all but four of these laboratories are compared using the Global Positioning System, GPS. Rough data are sent to the BIPM and treated according to strict common views in order to overcome Selective Availability effects [4, 5]. The general organization of the international GPS network used by the BIPM is shown in Fig. 2. It comprises:

- two long distance lines, linking three nodes: the NIST (USA), the OP (France), and the CRL (Japan), where GPS antenna coordinates are known accurately, and where ionospheric measurements are available. In addition, GPS data are corrected in post-processing with precise satellite ephemerides available from the International Geodynamics Service, IGS. For these two long-distance links (ge 6000 km) clock comparison noise is smoothed out for averaging times of order three days, and the overall accuracy is of order 6 ns to 8 ns (1 σ)[6].
- local stars on a continental scale. Ionospheric measurements and precise satellite ephemerides are not used for these short-distance links (le 1000 km), but accurate GPS antenna coordinates help to improve the accuracy obtained. Typically, clock comparison noise is smoothed out for averaging times of order 12 hours to 24 hours, and the overall accuracy is of order 2 ns (1 σ)[6].

The reference time scales TAI and UTC have been regularly computed and published in the monthly *Circular T* since the 1st January 1988, the date of official transfer of this responsibility from the old BIH to the BIPM. Annual reports are also produced by the BIPM Time Section, and have been available, in the form of computer-readable files, in the BIPM INTERNET anonymous FTP since 5 April 1994.

For years, the TAI scale interval has been regularly compared with the best realizations of the SI second provided by the primary frequency standards maintained at the PTB (Germany), PTB CS1 and CS2, which operate continuously as clocks. Their stated accuracies are respectively 3 $\times 10^{-14}$ and 1.5 $\times 10^{-14}$ (1 σ). Recently, two newly designed cæsium frequency standards, using optical production and detection of atoms have been evaluated:

- NIST 7, developed at the NIST (Boulder, Colorado, USA) reaches an accuracy of 1 $\times 10^{-14}$[7].
- JPO (Jet à Pompage Optique), developed at the LPTF (Paris, France) attained an accuracy of 1.1 $\times 10^{-13}$ when evaluated for the first time in May 1993[8].

The deviation of the TAI scale interval, to the SI second as realized by PTB CS1, PTB CS2, and NIST 7, is shown in Fig. 3 for the last three years. The JPO is not included because its uncertainty is much larger than that of other primary frequency standards. On average, this deviation is estimated to be of order 0.2 $\times 10^{-14}$, with an uncertainty of 11 $\times 10^{-14}$ (1 σ) for the two–month interval July–August 1994. Since April 1993, the TAI frequency has remained constant with respect to the best primary standards, so no frequency–steering corrections have been applied.

ALGORITHMS FOR TIME SCALES

The quality of the timing data used for TAI computation is rapidly evolving thanks to the wide use of GPS time transfer, and to the extensive replacement of older designs of commercial clocks by the new HP 5071A clocks and active auto–tuned hydrogen–masers. White measurement noise of distant time comparisons is thus smoothed out by averaging data on periods shorter than 10 days. In addition, the use of very stable clocks leads to a large improvement in the stability of TAI and UTC. By application of the N–cornered hat technique to the data obtained in 1993 and at the beginning of 1994, for the comparisons between TAI and the best independent time scales of the world (maintained at the NIST, the VNIIFTRII, the USNO and the PTB), one obtains the following estimates of stability (expressed in terms of Allan standard deviation and shown in Fig. 4):

$$\begin{aligned}
\sigma_y TAI\ (\tau = &\ 10\text{days}) = && 3.9 \times 10^{-15}, \\
\sigma_y TAI\ (\tau = &\ 20\text{days}) = && 3.2 \times 10^{-15}, \\
\sigma_y TAI\ (\tau = &\ 40\text{days}) = && 3.5 \times 10^{-15}, \\
\sigma_y TAI\ (\tau = &\ 80\text{days}) = && 4.9 \times 10^{-15}.
\end{aligned}$$

The stability of TAI and UTC lies thus below 5 $\times 10^{-15}$. It also appears that the basic interval of computation, at present 60 days, can be reduced. This, if done, will help to shorten the delay of access to TAI. We are thus testing a new version of the algorithm ALGOS for the definitive computation of TAI each month, using real data from the beginning of 1992. Results are encouraging and it has been decided that the CCDS working group on Improvements to TAI should meet in March 1995 to discuss this new algorithm.

An interesting point is that the same stability study carried out using EAL instead of TAI gives the following results:

$$\begin{aligned}
\sigma_y EAL(\tau = &\ 10\text{days}) = && 3.9x10^{-15}, \\
\sigma_y EAL(\tau = &\ 20\text{days}) = && 3.2x10^{-15}, \\
\sigma_y EAL(\tau = &\ 40\text{days}) = && 3.1x10^{-15}, \\
\sigma_y EAL(\tau = &\ 80\text{days}) = && 4.0x10^{-15}.
\end{aligned}$$

A degradation of the stability of TAI, for averaging times ranging from 40 days to 80 days, is apparent when compared with the stability values obtained for EAL. This is probably due to the single frequency steering correction of 5×10^{-15} carried out in April 1993. Clearly the amplitude of this frequency step was too large, given the size of EAL fluctuations. It follows that steering corrections should be small (probably of order 1 to 2×10^{-15}), and are useful only for modification of the TAI frequency in the very long term.

Given the high stability of recently designed commercial clocks and hydrogen–masers, it appears that it is now time to consider fundamental modification of the TAI algorithm. The next meeting of the CCDS working group on Improvement to TAI, scheduled for March 1995, is a good opportunity to discuss this topic. We are therefore studying, on real data, the following points:

- computation of TAI every 30 days instead of 60 days,
- introduction of a frequency drift evaluation in the frequency prediction of hydrogen-masers,
- change of the upper limit of weights,
- change of the weight determination procedure, which is at present based on the observation of systematic frequency changes with annual signature, a phenomenon which tends to disappear,
- danger of excessive dependence on a single clock type (HP 5071A),
- advantages of changing the basic measurement cycle from 10 days to 1 day,
- advantages of increasing or decreasing the number of participating clocks.

These studies have been partly reported[9, 10], and it is already expected that the shortening of the period of definitive computation and a better use of hydrogen masers will be recommended by the working group.

TIME LINKS

The BIPM Time section is interested in any time comparison method which has the potential for nanosecond accuracy. We are thus involved in the development of GLONASS, LASSO, two–way time transfer via geostationary satellites, and ExTRAS (Experiment on Timing, Ranging and Atmospheric Soundings, also named "hydrogen maser in space"), although GPS strict common–views remain the time transfer means used for current TAI computation.

Global Positioning System, GPS

Among its current activities, the BIPM issues, twice a year, GPS international common–view schedules, produces international GPS comparison values, and also publishes an evaluation of the daily time differences between UTC and GPS time. These differences were obtained by treatment of data from Block I satellites only. Since April 1994, only one Block I satellite has

been observable, and daily values have been obtained by smoothing data taken from the Block II satellites viewed at angles of elevation greater than 30°. The results are less precise than before (daily standard deviations of order 12 ns, against 3 ns) because Selective Availability is currently implemented. Although we have shown that precise restitution of GPS time is possible using multi-channel P-code GPS time receivers[11], this method cannot be used because reliable and regular data from such a receiver is not yet available.

An important part of our current work is to check the differential delays between GPS receivers which operate on a regular basis in collaborating timing centres, by transporting a portable GPS time receiver from one site to the other. Exercises in differential calibration of GPS receivers carried out in 1994 concerned the links between the OP (France) and the NPL (United-Kingdom)[12], the NIST (USA)[13], the USNO (USA)[14], and a European round-trip OP to OP successively through the OCA (France), the TUG (Austria), the FTZ (Germany), the PTB (Germany), the VSL (The Netherlands), and the NPL (United Kingdom)[15].

Since 1983, several differential calibrations have been performed between the NIST and the OP. The results are shown in Table 1.

Date t	δ/ns	σ/ns
July 1983	0.0	2.0
January 1985	-7.0	13.0
September 1986	+0.7	2.0
October 1986	-1.4	2.0
January 1988	-3.8	?
April 1988	+0.6	?
March 1994	+1.4	2.0

Table 1. Results of 7 exercises in the differential calibration of the GPS time equipment in operation at the NIST and at the OP. The quantity δ is the time correction to be added to the values UTC(NIST)(t) - UTC(OP)(t), obtained at date t from raw GPS data, in order to ensure the best accuracy of the time link. The quantity σ is the estimated uncertainty (1 σ) in the value δ.

In 1983 the internal delay of the OP GPS time receiver was determined at the NIST, before shipping to the OP, so that the time comparison values between UTC(NIST) and UTC(OP) could be obtained from GPS data without any systematic correction. This accuracy is maintained by applying time corrections δ which compensate for variations with time in the internal delays of the two pieces of GPS equipment. The values of δ remain inferior to their stated uncertainty (1 *sigma*) even after 10 years of continuous operation, which indicates the excellent long-term stability of the equipment.

For several years, GPS accuracy has also been studied by testing the closure condition through a combination of three links, OP-NIST, NIST-CRL and CRL-OP, using precise GPS satellite ephemerides and ionospheric delays measured at the three sites[6]. As shown in Fig. 5, the closure condition presents a residual bias of a few nanoseconds on daily averages which can

be determined with a precision of less than 2 ns. With the passage of time, the IGS precise satellite ephemerides continue to improve, which results in a corresponding improvement in the determination of the deviation from the closure. The residual bias now probably originates from errors in station coordinates and errors in ionospheric measurements. Results from codeless dual-frequency ionospheric measurement systems are sensitive to multipath effects which induce biases in particular directions[16]: these biases are not averaged when testing the closure condition if the observations selected are directed towards the East and West. Work is under way to evaluate these biases.

Within the group on GPS Time Transfer Standards, GGTTS, the BIPM has made a considerable effort to formulate technical directives for the standardization of GPS time-receiver software, together with a new format for GPS data files[17, 18]. The implementation of such directives and of the new data format should help to provide sub-nanosecond accuracy for GPS common-view time transfer. Practical development of the standardized software is in hand at the NIST and it is intended that it will be available for world-wide use from beginning of 1995[19].

Another issue is the estimation of the tropospheric delay. At present, GPS time-receivers use simple models of the troposphere which, as was believed until recently, should provide an estimation of tropospheric delay with an uncertainty of 1 ns to 2 ns. Recent comparisons of these models with a semi-empirical model based on weather measurements show, however, differences of several nanoseconds for hot and humid regions of the world[20]. Further investigations of the tropospheric delay will continue at the BIPM.

GLObal NAvigation Satellite System, GLONASS

Values of comparison between UTC and GLONASS time, provided from observations of GLONASS satellites by Prof. P. Daly, University of Leeds, are currently published in the *BIPM Circular T*. The BIPM intends to issue an experimental international GLONASS common-view schedule in 1995, and to test it through an experiment with the RIRT, Russia. For this purpose, the BIPM will receive a GLONASS time receiver on loan from Russia.

Two-Way Satellite Time Transfer, TWSTT

Two-way time transfer through a geostationary satellite is potentially more accurate than one-way methods such as those using GPS or GLONASS, essentially because there is no need to evaluate the range between ground station and satellite. No two-way time transfer experiment has been conducted at the BIPM, which does not possess the necessary heavy equipment, however, the BIPM does chair the CCDS working group on Two-Way Satellite Time Transfer, which meets every year, and was involved in the comparison between the two-way technique and the GPS common-view method which used the link between the TUG (Austria) and the OCA (France)[21]. The BIPM was also involved in the field-trial which was organized in 1994. This is an international two-way time transfer experiment through the INTELSAT V-A(F13) satellite at 307°E, which involves both European and North-American laboratories. This began in January 1994 and should last one year. During the summer of 1994, the Earth stations involved have been calibrated using a portable station. At the same time, the GPS equipment in these laboratories was differentially calibrated using a portable GPS time receiver provided

by the BIPM. These calibration exercises should allow previous estimates of the accuracy, of order 2 ns (1 s), of the two–way technique to be verified[15].

LAser Synchronization from Satellite Orbits, LASSO

The BIPM has been involved in an experiment to compare time transfer by LASSO with GPS common–view time transfer between Texas and France[22]. The results of the calibration of laser equipment at the two sites should be available at the end of 1994 and will allow, for the first time, an estimation of the accuracy of the LASSO technique, which is expected to be of order 1 ns (1 σ).

Experiment on Timing Ranging and Atmospheric Soundings, ExTRAS

The Experiment on Timing Ranging and Atmospheric Soundings, ExTRAS, calls for two active and auto–tuned hydrogen masers to be flown on board a Russian meteorological satellite Meteor–3M, planned for launch at the beginning of 1997. Communication between the on-board clocks and ground stations is effected by means of a microwave link using the PRARE technique, Precise Range And Range–rate Equipment, and an optical link operating using the T2L2 method, Time Transfer by Laser Link. The PRARE and T2L2 techniques are upgraded versions of the usual two–way and LASSO methods. Associated with the excellent short–term stability of the on–board hydrogen masers, these should make it possible to solve a number of scientific and applied problems in the fields of time, navigation, geodesy, geodynamics and Earth–atmosphere physics. The impact of ExTRAS in the time domain, has been studied[23] in terms of anticipated uncertainty budgets: the potential accuracy of this experiment is characterized by uncertainties below 500 ps (1 σ) for satellite clock monitoring and ground clock synchronization.

APPLICATION OF GENERAL RELATIVITY TO TIME METROLOGY

An investigation of the application of the theory of relativity to time transfer has been completed[24]. Explicit formulae have been developed, which make it possible to compute, to picosecond accuracy, all terms describing the coordinate time interval between two clocks situated in the vicinity of the Earth, and linked through *i*) a one–way technique (GPS), *ii*) a two–way method via a geostationary satellite (TWSTT), or *iii*) a two–way optical signal (LASSO).

Current work centers on the application of the theory of relativity to the frequency syntonization of a clock with respect to the Geocentric Coordinate Time (TCG) at an accuracy level of 10^{-18}. For Earth–bound clocks, this is limited to some parts in 10^{17} due to poor knowledge of some geophysical factors (essentially the potential on the geoid). However, for clocks on terrestrial satellites, all terms can be calculated with 10^{-18} accuracy. The results of this work will allow the establishment of a complete relativistic framework for the realization of TCG at a stability of 10^{-18} and picosecond TCG datation accuracy. This should be sufficient to accommodate all expected developments in clock technology and time transfer methods for some years to come.

The work of the CCDS working group on the Application of General Relativity to Metrology was supported by numerous discussions with Prof. B. Guinot, Chairman of the working-group, and participation in the preparation of a text to be used as part of the final report of this group.

PULSARS

Millisecond pulsars can be used as stable clocks to realize a time scale by means of a stability algorithm. Work has been carried out with a view to understanding how such a pulsar time scale could be realized and how it could be used for monitoring very-long instabilities of atomic time. An important feature of this work is that a pulsar time scale could allow the transfer of the accuracy of the atomic second from one epoch to another, thus overcoming some of the consequences of failures in atomic standards[25].

CONCLUSIONS

The Time Section of the BIPM produces time scales which are used as the ultimate references in the most demanding scientific applications. They serve also synchronization of national time scales and local representations of the Coordinated Universal Time, upon which rely all time signals used in current life. This work is thus is complete accordance with the fundamental missions of the BIPM.

Timing data used to generate the International Atomic Time comes from national metrological institutes where timing equipment is maintained and operated in the best conditions. An international collaboration is thus necessary and requests from the contributing laboratories to follow guides given by the BIPM. In return, the BIPM has the duty to process data in the best way in order to deliver the best reference time scales. For this purpose, it is necessary for the BIPM to examine in detail timing techniques and basic theories, to propose alternative solutions for timing algorithms, and to follow advice and comments expressed inside the CCDS working groups.

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Acronyms of the laboratories quoted in the text

CRL	Communications Research Laboratory, Tokyo, Japan
FTZ	Forschungs – und Technologiezentrum, Darmstadt, Germany
LPTF	Laboratoire primaire du Temps et des Fréquences, Paris, France
NIST	National Institute of Standards and Technology, Boulder, CO, USA
NPL	National Physical Laboratory, Teddington, United Kingdom
OCA	Observatoire de la Côte d'Azur, Grasse, France
OP	Observatoire de Paris, Paris, France
PTB	Physikalisch–Technische Bundesanstalt, Braunschweig, Germany
RIRT	Russian Institute of Radionavigation and Time, St. Petersburg, Russia, Austria
TUG	Technische Universität, Graz, Austria
USNO	U.S. Naval Observatory, Washington D.C., USA
VSL	Van Swinden Laboratorium, Delft, The Netherlands

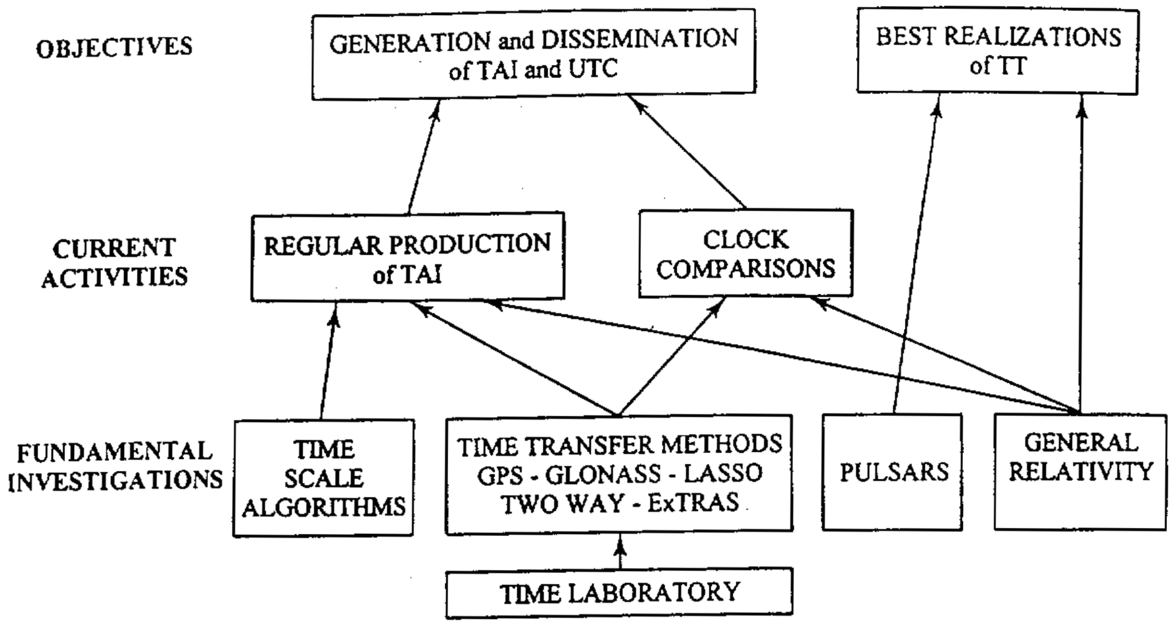

Figure 1. Organization of the work of the Time Section of the BIPM

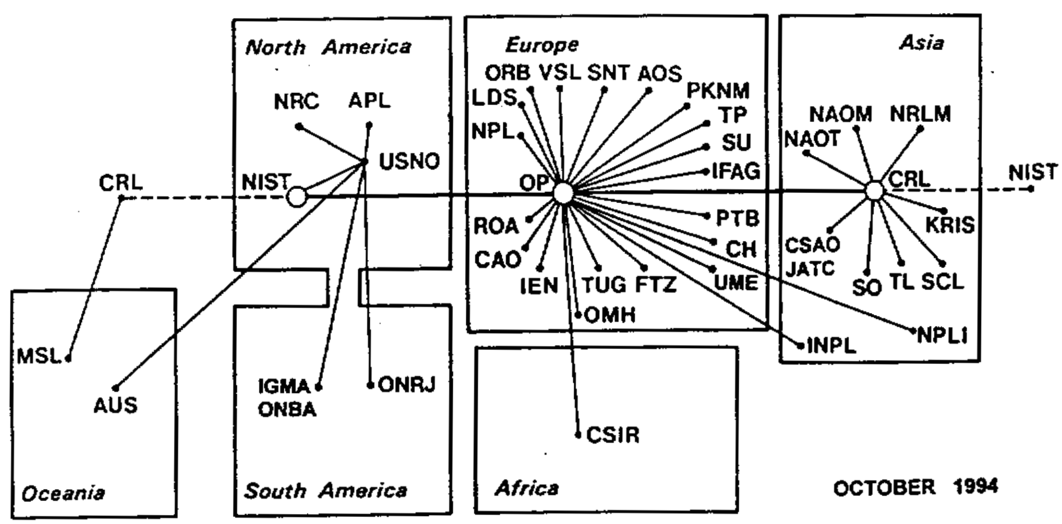

Figure 2. Organization of the international GPS time link network used for TAI computation (October 1994). Acronyms can be found in Table 3 of the *Annual Report of the BIPM Time Section*, Volume 6, 1994.

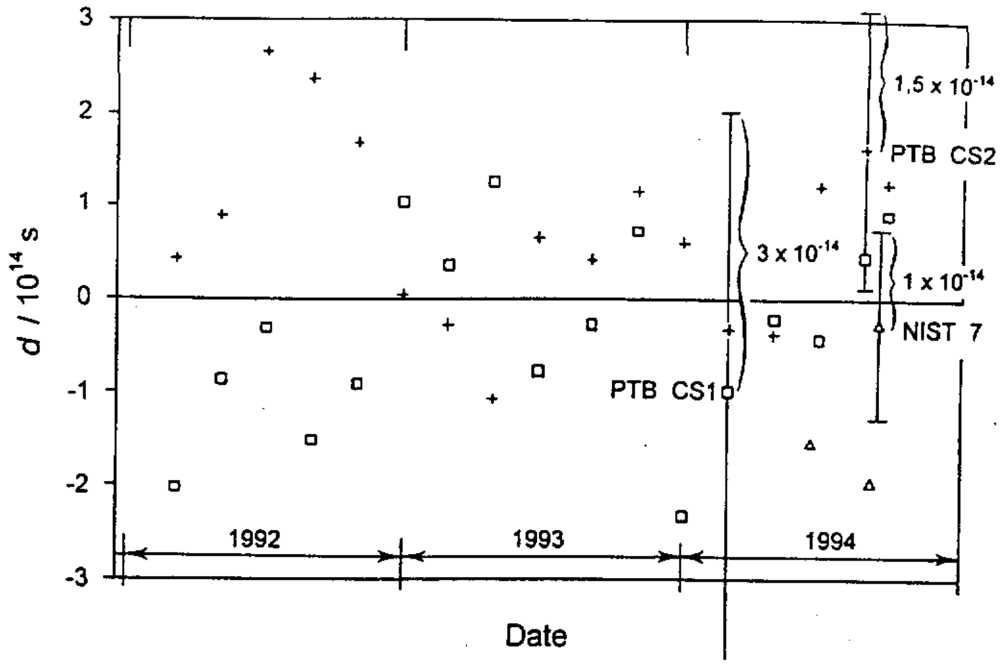

Figure 3. Deviation d of the TAI scale interval from the SI second on the rotating geoid, as provided by the primary frequency standards PTB CS1, PTB CS2, and NIST 7 (error bars correspond to the published uncertainty 1 σ).
Recall that the frequency of NIST 7 is corrected for the black body radiation shift while those of PTB CS1 & 2 are not.

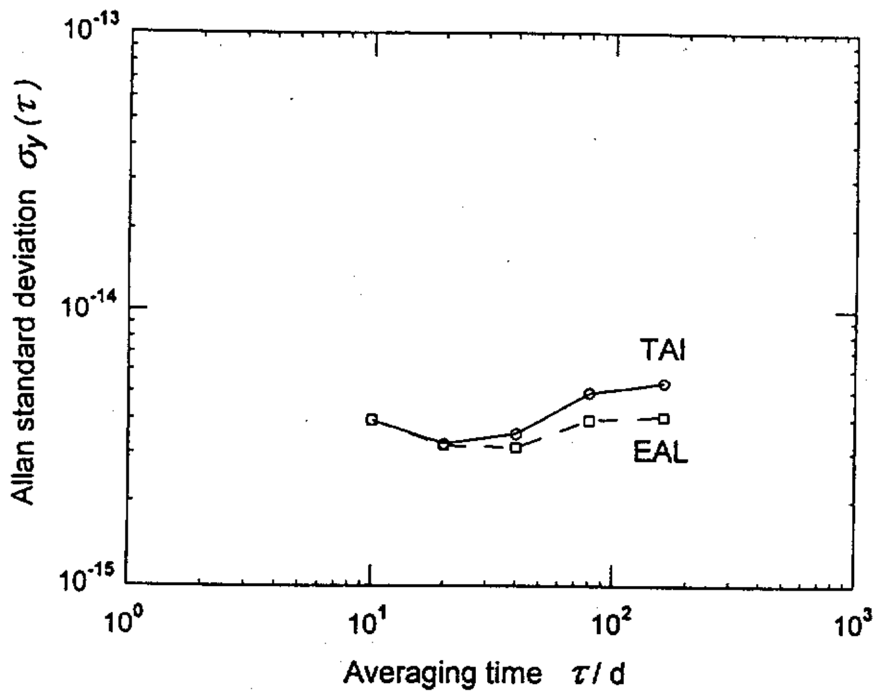

Figure 4. Stability of TAI and EAL.
Allan standard deviations obtained by application of the N-cornered hat technique to data obtained in 1993 and at the beginning of 1994, for the comparisons between TAI and the time scales maintained at the NIST, the VNIIFTRII, the USNO and the PTB.

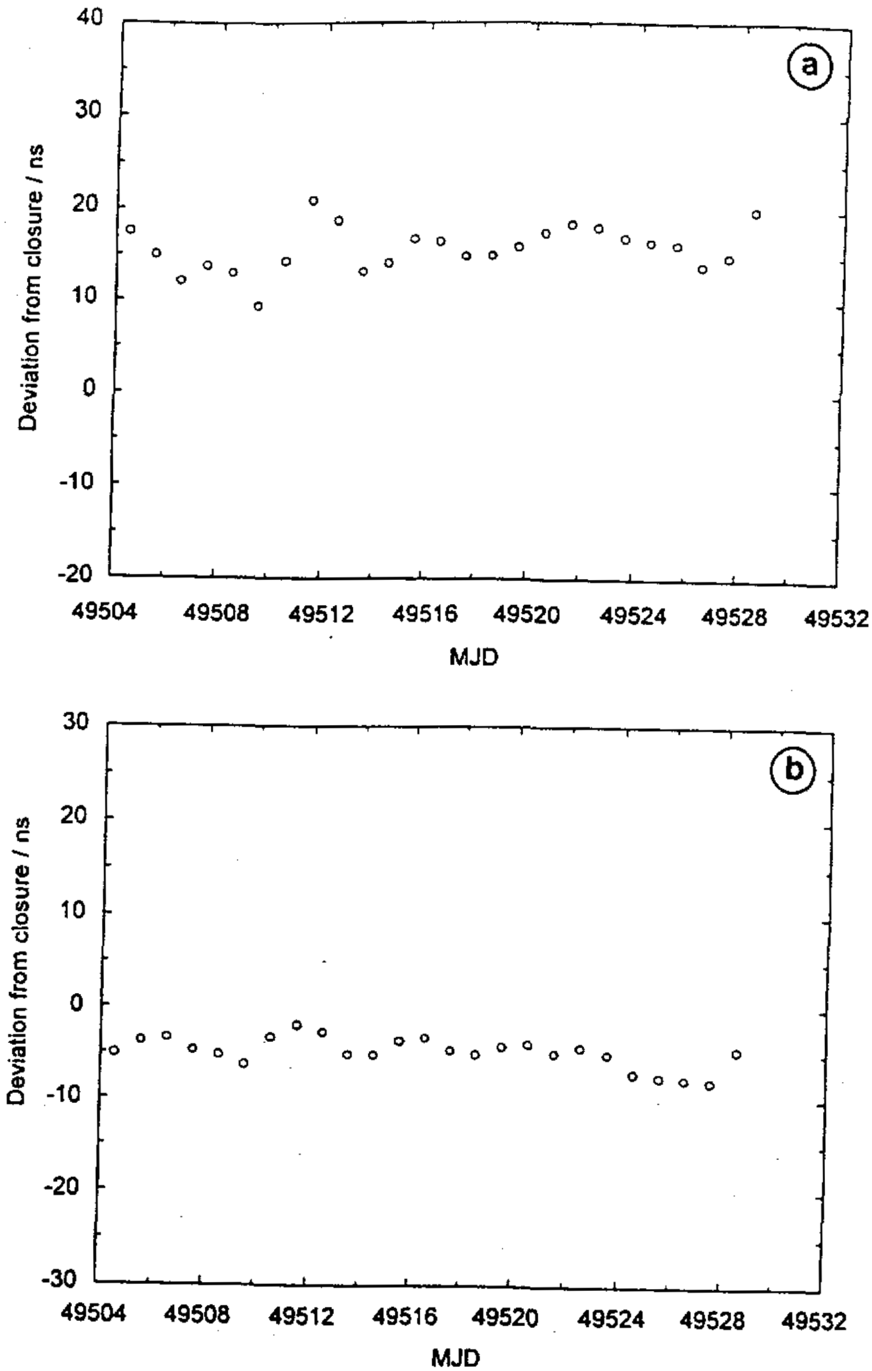

Figure 5. Deviation from the closure around the world obtained from GPS common-views between the OP and the CRL, the CRL and the NIST, and the NIST and the OP. The sum of these three links is computed:

in Fig. 5.a. with raw GPS data and amounts to (15,7 ± 2,6) ns, and

in Fig. 5.b. with GPS data corrected for measured ionospheric delays and post-processed precise satellite ephemerides, and amounts to (-4,8 ± 1,6) ns.

QUESTIONS AND ANSWERS

GERNOT M. WINKLER (USNO): In your presentation, you showed the definition of TAI. I find it remarkable, the sentence which I forgot in the meantime, and that is in conformance with the definition of the second. That has, of course, direct implications regarding the use of hydrogen masers. Could you maybe comment on that?

CLAUDINE THOMAS (BIPM): This is the first definition from 1971. Of course, there were other definitions which have been -- this definition has been updated in time. Now it is exactly stated that the scale unit of TAI must be as close as possible to the SI second as realized on the rotating geoid. So the word "in accordance" -- but that's a question. You know that we have national laboratories which think that we shouldn't use hydrogen masers in computing TAI because they are using the hydrogen atomics instead of the cesium atom. That's something to be discussed.

FRED WALLS (NIST): I would like to address that. Using a hydrogen maser is no different than using the commercial cesium standard which does not have the same accuracy of the primary standards in the national labs. What you need for the short term are flywheel oscillators that are stable; it doesn't matter if they're based on calcium, if they're based on mercury, if they're based on hydrogen or any other atom, if you have something which is very stable. They're just a flywheel. The definition of the second comes at the present time from large primary standards and national laboratories. That can be used to establish frequency in the long term, as you do now.

So I do not see any conflict at all.

CLAUDINE THOMAS (BIPM): Atomic hydrogen masers are very stable. And, of course, they cause the stability of TAI. But they must be used carefully in the particular case where they show a drift relative to some primary system frequency standards. This drift, should be evaluated and calculated in the algorithm, of course.

FRED WALLS (NIST): Yes, I agree with that. But something quite serious which you only partially alluded to is we must agree internationally on whether or not to include the black body radiation. That is something that's on the order of $2 \rightarrow 4 \times 10^{14}$; and it's quite serious at the level of accuracy that the national scales are now. We must come to some agreement. I think it should be included, in my opinion.

CLAUDINE THOMAS (BIPM): Well this is something which will be discussed next March during the meeting of the working group on the improvement of TAI. There are many questions to discuss, and, in particular, using data from these new test tables and accurate primary frequency system standards and how to correct them.

HARRY PETERS (SIGMA TAU STANDARDS): The National Radio– astronomy has 12 hydrogen masers, 10 of them are stationed from the Hawaiian Islands to the Virgin Islands; they are operating continuously and many of them have been going since 1987. I have been encouraging them to try to keep a record of time; they don't vary their synthesizers. And it seems to me that this is an asset that could possibly be included in the international time scale if they could just improve the record–keeping and perhaps transmit the information to you.

Thank you.

GERNOT M. WINKLER (USNO): I would like to come back to the question of the black body radiation. Because, this is an extremely important point, and it should be discussed as much as possible. An objection has been raised to the inclusion of that at the present time, before any experimental verification exists. The question is, is there an effort going on anywhere to demonstrate, at least in a quantitative way, the existence of that effect? Since the effect goes with the fourth power of temperature, it shouldn't really be too difficult to make a test, even within obtainable laboratory conditions -- different between, for instance, an operation of 10 degrees C. and 40 degrees C. should be substantial. Do you have any comments on that?

THOMAS PARKER (NIST): I'm not really the person to be doing this, but they're beginning to think about how to try and do that with NIST 7. It's pushing the limits of what we can do, but they are beginning to make some plans to try and see how far they can make an evaluation of the black body radiation. It's not clear that we're in position to really get a good number on that yet.

DAVID ALLAN (ALLAN'S TIME): Actually two comments, I guess. Maybe one is a question. I believe the linear mercury ion trap at JPL, because of its excellent long-term stability, is in a good position to measure the black body radiation. So I put a question to JPL in that regard.

The other point I wish to make is picking up on Dr. Winkler's question about hydrogen masers. Very often, even with cavity servos, in very long term we see frequency drift, as you alluded to. And it's one thing to include it, it's another thing to ask what is the uncertainty on the estimate. And that has not been addressed well. But these are important questions for TAI because of the need for long-term performance.

CLAUDINE THOMAS (BIPM): We use it on real data at the BIPM for the moment. And it appears that it is not always easy to detect a minor drift.

FRED WALLS (NIST): If you look at the drift that's been estimated for a lot of the hydrogen masers, it's within one or two sigma of what the accuracy claimed at the national labs for their primary cesium standards averaged over one or two years. It's so small that at this point I find it very difficult to believe the estimate on the drift on the hydrogen masers. The drift may, in fact, be zero for some of them, maybe for many of them.

So even though there is some difference -- and you say parts in 10^{17} per day averaged over a year or two, that's within the one sigma limit of accuracy claimed at PTB and at NIST, and NRC and whatever.

CLAUDINE THOMAS (BIPM): The thing I can tell you about that is that we have tried to compute another version of EAL at various times, without any hydrogen maser. And it gives something which seems to have a lower drift. So maybe hydrogen masers adds some drift to EAL. But, of course, we are missing about 30 clocks when we do not use hydrogen masers. So, that's another point.

SIGFRIDO M. LESCHIUTTA: Before I give the floor to Dr. Winkler, I want to make a comment. There are a huge numbers of questions, and some of those questions are double

questions. I think the time is right for discussions for the people inside the national laboratories to talk about the next meeting to be held in Paris. If I remember correctly, that meeting will be convened by Dr. Winkler, since you are chairman of that activity. Do you want, Dr. Winkler, to add some additional remarks?

GERNOT M. WINKLER (USNO): Yes. In fact, thank you for these comments, because these are essentially the main points which will be discussed. And that meeting would be more productive if the participants coming from the laboratories receive any ideas which exist in regards to these points.

Coming back to the question of drifts, on the basis of a considerable number of clocks -- and 12 of them are Sigma Taus at the Observatory -- I have come to the conclusion that there is no zero. There is no clock which has a zero drift. In other words, any clock has sometimes changes in its structure or any observation which sometimes comes up as different values; so that at a level of our capability today, it is impossible to state that there is any clock which has zero drift.

Going back to the hydrogen maser, for instance, it is quite possible that the process which controls the cavity tuning, which is based on the measurement of the hydrogen line itself, is disturbed by effects which come from the cavity coating. And that is an effect which possibly has to do with chemistry changes in the surface. There are all kinds of things. In other words, as we go down in our level of precision to smaller and smaller values, we find more and more effects which can make a change and which do not always exist. And we have to realize that there is a difference between our ideas, which are ideal, of course, and to reality, which is infinitely complex and which you have to remember.

HARRY PETERS (SIGMA TAU STANDARDS): I think one point that is a serious point is that one should possibly look at this from an astrophysical point of view or a structure–of–the–universe point of view; after all, the universe is suppose to be expanding at a part of 10^{10}; or effectively, we are shrinking, as another view of it, at a part of 10^{10} per day. There is no absolute knowledge of whether the relative frequency of hydrogen and cesium are not changing fundamentally, due to conventional changes or whatever. I mean, we don't know that hydrogen absolutely does not change them slightly or change them in regard to cesium at 10^{-14}, well, maybe 13 or 15. So there is that absolute question of are all these transitions really constant and you must choose one, I suppose..

SIGFRIDO M. LESCHIUTTA: Certainly, Dr. Peters, you are opening quite a large program. I know that some activities are underway in some laboratories comparing fine transitions with hyperfine transitions. And some activities are now in Europe, and most in the United States. Basic physics is a wonderful thing. I fully agree with you that the program you described is opening new question marks.

CLAUDINE THOMAS (BIPM): I would like to make a comment about the last point made by Dr. Winkler. Of course, before the meeting I will write down all studies which have been done at the BIPM on real data. It does not cover all the questions, but we will make reports and send those reports to people who will be there. This might be a first attempt to answer these questions.